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Lessons for an invisible future from an invisible past: Risk and resilience in deep time

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Abstract

The interrelated concepts of risk and resilience are inherently future-focused. Two main dimensions of risk are the probability that a harmful event will happen in the future and the probability that such an event will cause a varying degree of loss. Resilience likewise refers to the organization of a biological, societal, or technological system such that it can withstand deleterious consequences of future risks. Although both risk and resilience pertain to the future, they are assessed by looking to the past – the past occurrence of harmful events, the losses incurred in these events, and the success or failure of systems to mitigate loss when these events occur. Most common risk and resilience measures rely on records extending a few decades into the past at most. However, much longer-term dynamics of risk and resilience are of equal if not greater importance for the sustainability of coupled socioecological systems which dominate our planet. Historical sciences, including archeology, are critical to assessing risk and resilience in deep time to plan for a sustainable future. The challenge is that both past and future are invisible; we can directly observe neither. We present examples from recent archeological research that provide insights into prehistoric risk and resilience to illustrate how archeology can meet this challenge through large-scale meta-analyses, data science, and modeling.

Keywords

archeology, data science, Early-Holocene, Mediterranean, MedLanD, Mid-Holocene, modeling, Pleistocene, prehistory, resilience, risk, socioecological systems

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Thinking about risk and resilience

Risk and resilience are broad concepts relevant to understanding the dynamics of human societies and the interactions between societies and their environments – today and in the past. The concept of risk can be applied to nearly all aspects of human life, of course, and is formally employed in economics, engineering, and the global insurance industry, for example. Resilience is a concept of more recent widespread use, particularly in relation to sustainability and climate change. The use of these concepts in archeology is variable but not insignificant. For example, Table 1 shows numbers of papers with the terms *risk* or *resilience* in six leading English-language archeological journals in comparison to the total numbers of papers published in those journals over the past four decades. Figure 1 presents the same data over time, in more detail, from the two journals in Table 1 with the largest numbers of papers published: *Journal of Archeological Science* and *Antiquity*.

Risk

It is clear from Figure 1 that the concept of risk has appeared for at least the past 40 years, initially at low but growing frequency. An early discussion of risk in deep time is Robin Torrence's study of technology, in particular lithic technology, as a means to reduce risk (Torrence, 1989). An ongoing focus has been on how past societies have been impacted by *external risks*, such as from rapid environmental change (Cooper and Sheets, 2012). To make use of the concept of risk in deep time, it is important to remember that it involves two independent dimensions: "the probability of a bad thing occurring and an estimate of just how bad that bad thing is." (Bamforth and Bleed, 1997: 112). There is also a very different form of risk, *systemic risk*, that has begun to be discussed with increasing frequency but which is largely absent from the archeological literature so far. Systemic risk refers to the potential for complex systems[1] to undergo unexpected, rapid or catastrophic, reorganization or even collapse due to endogenous couplings, interactions, and feedbacks among their component parts (Bentley and Maschner, 2007; Haas et al., 2022; Haimes, 2018; May et al., 2008). Related is the concept of *critical transitions* whereby a system experiences rapid and often non-recoverable systemic change due to an accumulation of risk factors, such as increased homogeneity and interconnection (Scheffer et al., 2009). While studied mainly in relation to global financial systems at present, systemic risks are inherent in any complex system, including human societies and socioecological systems, making this concept relevant for

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Table 1. Frequency of papers mentioning risk and resilience in leading archeological journals (Source: Google Scholar, June 2022).

Archeological journal	Scopus impact scores	Papers published 1980–2022	Papers mentioning risk	Papers mentioning resilience	Papers mentioning risk & resilience
			N (%)	*N* (%)	*N* (%)
Journal of Archeological Research	5.16	360	108 (30.0)	34 (9.4)	21 (5.8)
Journal of Archeological Science	3.53	10,500	1390 (13.2)	368 (3.5)	122 (1.2)
Journal of World Prehistory	3.48	364	78 (21.4)	16 (4.4)	9 (2.5)
Journal of Archeological Method and Theory	3.18	1758	214 (12.2)	80 (4.6)	47 (2.7)
American Antiquity	2.63	8140	776 (9.5)	189 (2.3)	53 (0.7)
Journal of Anthropological Archeology	2.22	1390	429 (30.9)	135 (9.7)	66 (4.7)
Antiquity	1.71	32,600	3170 (9.7)	511 (1.6)	139 (0.4)
European Journal of Archeology	1.59	1730	186 (10.8)	34 (2.0)	11 (0.6)
Totals		56,842	635 (11.2)	1367 (2.4)	468 (0.8)

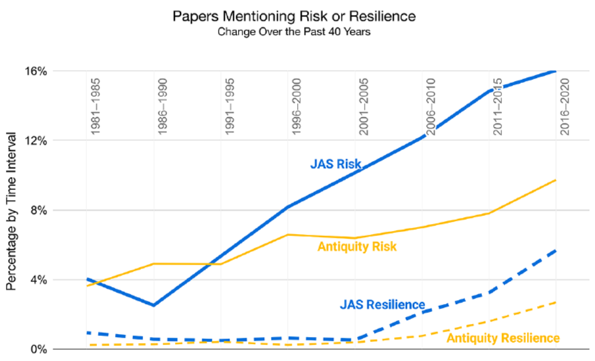

Figure 1. Percentage of papers mentioning risk and resilience in the *Journal of Archeological Science* and journal *Antiquity* over a period of 40 years, out of all papers published in each time interval (Source: Google Scholar, June 2022).

understanding past societal dynamics (Brovkin et al., 2021; Kemp et al., 2022; Tainter, 2006).

Resilience

Resilience, as a concept in ecology, was introduced by Holling (1973) 50 years ago, but was almost never mentioned in archeological context prior to 2006. It has appeared in the archeological literature increasingly since then, however, chronologically following the seminal papers by Redman (2005), and Redman and Kinzig (2003). Building on Holling (2001), they discuss the relevance of "Resilience Theory" (RT), including Gunderson and Holling's *Panarchy* model (Gunderson and Holling, 2001; Holling, 2001), for understanding long-term patterns of change and stability in human societies. They refer to the concept of resilience itself as "the ability of a system to remain *functionally stable* in the face of stress and to recover following a disturbance." [emphasis added] (Redman and Kinzig, 2003: 5). In its wide usage, the term resilience has come to refer to a number of loosely related processes, with debate over its meaning and application to ecosystems and social systems (Jacobson, 2022; Peeples et al., 2006; Rashidian, 2021; Van Meerbeek et al., 2021). It is not our aim to review or critique this large and varied literature. Fortunately, Martin-Breen and Anderies (2011) provide a comprehensive review in which they group the ways in which resilience has been used into three related concepts. *Engineering resilience* is the ability of a system to return to its former state after some kind of stress or shock – the way in which Redman and Kinzig use the term. *Systems resilience*, also referred to as robustness, refers to the ability of a system to maintain its fundamental organization and critical functions in the face of some disturbance or environmental change, including long-term disturbance or stresses. *Complex systems resilienc*e, or adaptive capacity, is the ability of a system to respond dynamically to stress or shock and recover or maintain critical functions, even if it involves reorganization or change of system structure to do so. That is, biological and social systems can evolve over varying timeframes in order to adapt to changing environmental conditions. All three of these kinds of resilience are useful for understanding the processes that drive long-term patterns of change and stability in human systems.

Relating risk and resilience

Risk and resilience are related in several important ways. At the most general, resilience for humans is a way of managing risk through some combination of cultural knowledge, social practices, and technology. The capacity of a system to recover from shocks is a function of the frequency of disturbance events and their severity. While people can control the likelihood of some kinds of risks, airplane crashes for example, they have little control over others, like earthquakes (Sheets and Cooper, 2012). Especially for pre-industrial societies, increasing resilience most often involved mechanisms to mitigate the severity of system shocks whose occurrence could not be altered but might be anticipated. For example, increasing resilience to drought in pre-industrial agricultural societies involved ways to reduce its impacts on agricultural food supplies, including cultural knowledge of past frequency of droughts and their impacts, social practices like food redistribution mechanisms, and technologies like grain storage and irrigation (e.g. Nelson et al., 2006; Peeples et al., 2006; 200; Strawhacker et al., 2020). Likewise, hunter-gatherers can change mobility strategies, shift the diversity of resources collected, and use more effective hunting and gathering technologies to mitigate the impacts of drought or other environmental changes (e.g. Barton et al., 2018; Freeman and Anderies, 2012). Cumulative cultural knowledge, shifts in social organization, and technological innovations over the long-term can increase adaptive capacity (e.g. McIntosh, 2000). Similarly, changes in settlement (e.g. temporary camps to villages), subsistence practices (harvesting wild resources to food production), and technological organization (e.g. use of animal labor and specialist production) enabled humans to survive major environmental disruptions of the Pleistocene/Holocene transition and support greatly increased populations although also transforming human society (Little et al., 2023).

While social and technological solutions can mitigate risk and increase resilience, they come with tradeoffs. Not only is it impossible to mitigate all possible risks, but efforts to mitigate one form of risk may well increase vulnerabilities to a different risk. For example, increasing investment in and dependence on irrigation can reduce the risk of food shortfalls during droughts. But this same system becomes increasingly vulnerable to floods and to social disruptions that reduce cooperation needed to maintain increasingly extensive and complex irrigation systems (Anderies, 2006; Graybill et al., 2006; Lustig et al., 2018).

Risk and resilience are related in another way that is especially important for archeology: evaluating both requires historical data. Actuarial data used by the insurance industry to estimate the likelihood of events causing loss and the potential magnitude of loss is based on analyses of similar past events and their contexts – from car accidents, to hurricanes, to kidnappings. In manufacturing and engineering, risk of failure is based on past performance of materials and components in laboratory and real-world settings. The data on which most risk assessment is based today extend from a few hours to a few decades into the past. However, there are many significant risks that play out over much longer time spans (Lyon et al., 2022). Estimating risks of earthquakes or volcanic eruptions, both frequency and magnitude, require data extending centuries into the past (e.g. Mani et al., 2021). To assess the risks related to the rate of sea level rise today, it is necessary to seek comparative data from the beginning of the Holocene, some 10 millennia in the past (Brovkin et al., 2021). And to begin to evaluate the environmental risks resulting from estimates of global temperatures by the end of the century, we must collect data from the last Interglacial, over 100,000 years ago, or even earlier (Kemp et al., 2022).

Systemic risk, arising from interactions and feedbacks among components of complex systems, cannot easily be measured from historical data alone. A major component of systemic risk is uncertainty due to stochastic or emergent properties of the system. Because this involves non-linear and potentially indirect relationships between causes and effects, standard archeological analyses are insufficient alone for measuring systemic risk, but data about past systems can still be useful. Methods helpful for assessing systemic risk are discussed in more detail below.

Like risk, resilience cannot be accurately evaluated without reference to the past. That is, it is difficult to estimate the ability of a social, ecological, technological, or other system to recover from shocks without baseline data on how that system or a similar one *did* (or did not) recover from past shocks. This is even more the case with long-term adaptations that are involved in systems resilience and complex systems resilience, and especially in response to low frequency shocks and long-term stresses.

Risk and resilience in the past and future

Risk and resilience are concepts in which the past and future meet. Most analyses of the past to assess risk are aimed at estimating the likelihood and magnitude of future events. Similarly, studies of past examples of resilience are directed at ways to be resilient when confronted by future shocks. Yet both the past and future are invisible lands. We hope to use the invisible past to shape the invisible future.

While the future exists only in our imaginations, we have more concrete access to the past, through memories of the living and the artifacts (written and otherwise) of the past beyond living memory. However, for complex, interacting, and dynamic social and living systems, the future is rarely like the past – especially over time frames of years, decades, centuries, or longer. Human culture, society, and its environmental context are constantly evolving, meaning that estimates of risk and resilience derived from simple linear projections of past events can be disastrously wrong. This is becoming increasingly apparent for climate related risks like extreme weather events, crop harvests, wildfires, and flooding that have been calculated previously on the basis conditions of the past century (e.g. Gent, 2022; Gholami et al., 2021; Mosavi et al., 2018; Popa et al., 2019).

It is important, then, to understand the underlying processes and structural arrangements that generated risks and promoted resilience in the past, rather than simplistic counts and projections. By focusing on the drivers of risk and resilience in deep time, archeological research has the potential to derive generalizable principles that can be highly useful in helping to assess future risks, especially significant risks that occur rarely or over long time frames, and devise strategies to increase our societal resilience (Kemp et al., 2022). In the following sections, we present brief case studies based on prior research in which we've been involved, reassessed from the perspective of understanding risk and resilience in deep time.

Archeological case studies

Resilience and biocultural evolution

Much of human evolutionary history has taken place in the context of an environmentally varying, glacial world. Beginning in the late Pliocene, our planet began a long-term period of cooler and drier terrestrial climate compared with prior epochs. There have been regular cycles of greater cooling within this time frame, interspersed with shorter intervals of global warming, driven proximately by synchronicities in Earth's orbital and rotational eccentricities, called Milankovich Cycles (Hays et al., 1976). During the past million years, these cycles have become more intense and regular, expressed as approximately 100ka cycles of a brief interglacial of ca. 10ka, followed by a much longer glacial period of increasingly cool temperatures and spread of continental ice sheets (Lee et al., 2017).

Although humans evolved biologically as a tropical/subtropical primate, there is widespread evidence that by over a million years ago our genus, *Homo*, had spread to the temperate zone of Europe and Asia, at least during interglacials (Ferring et al., 2011). Evidence that humans continued to occupy temperate locales during glacial periods is rare before the last Glacial/Interglacial cycle (López-García et al., 2021), but there are numerous sites with archeological materials and even human remains that date to the Last Glacial (ca. 119ka−11.6ka) across temperate Eurasia.

Although climate always varies over time, interglacials are periods of comparative climatic stability (excepting anthropogenic impacts of the past two centuries), while glacials are characterized by more extreme and often rapid fluctuations (Figure 2). These oscillations affected means, extremes, and distribution of temperatures and precipitation, as well as distribution and abundance of plants and animals. They created conditions of high environmental uncertainty over evolutionarily short time spans of decades and centuries rather than millennia, resulting in risk in terms of both the likelihood and magnitude of resource shortfalls and rigorous physical conditions of high stress for humans as a tropical species. Human behavioral flexibility and technological capacity for environmental modification are unsurprising, then, when so much of our biological and cultural evolution has taken place under these conditions. By the last interglacial, temperate zone human populations employed a suite of risk-mitigating technologies that allowed them to survive and thrive under environmental uncertainty of glacial conditions: including stone, wood, and bone technologies that enabled them to acquire and process a wide range of resources, including hunting of large ungulates; and using animal skins to protect their bodies from cold, the ability to construct shelters, and the control of fire to create localized tropical conditions.

Another important way that foragers use to mitigate risk of resource shortfalls is through mobility and land use strategies – how human groups distribute themselves across the landscape in space and time. Many hunter-gatherers, and especially those living in tropical/subtropical environments that are the original human habitat, are central-place foragers characterized by what is termed residential mobility (Binford, 1980; Grove, 2009; Kelly, 1995). They establish a camp in a locale with locally abundant

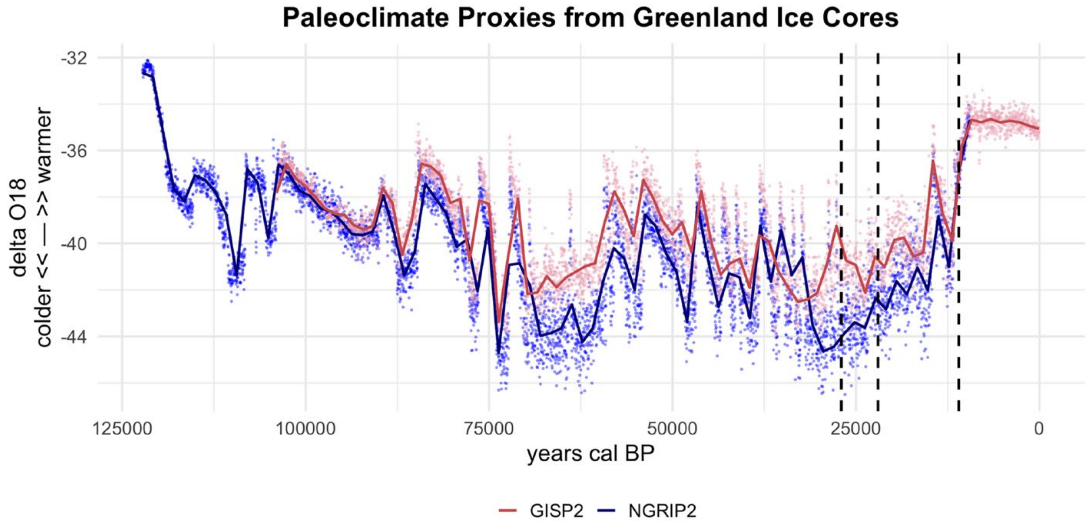

Figure 2. Paleotemperature proxy of ^{18}O concentrations in Greenland ice cores GISP and NGRIP (Rasmussen et al., 2008). Vertical dashed lines indicate periods of demographic decline discussed in the second case study and illustrated in the SPD analyses of Figure 5.

resources and then collect those resources from a relatively limited foraging radius around the camp. When resource abundance falls below some threshold, the camp is shifted to a new locale with more resources.

While this strategy is a highly resilient one in many contexts, it is less able to mitigate subsistence risk when resource abundance is very patchy with locations that shift in space and time. Among recent foragers, this is the case in high-latitudes where much human-edible biomass comes from large ungulates that congregate in large, but widely spaced herds whose locations can vary greatly over time. An alternative land use strategy, termed logistical mobility is often practiced in these ecosystems (Binford, 1980; Grove, 2010a). A central base camp is established with access to some important stationary resources like water. But other resource acquisition, especially hunting, is done by small groups that set out on long-distance expeditions to locate and kill mobile herd ungulates (or marine mammals), field-process the meat, and return it to the base camp. While the individuals involved in these resource forays can range over long-distances, logistical base camps are more stable and move less often than those of residential foragers.

There is considerable variation in the distance foragers travel to acquire resources, the lengths of time camps are occupied, and the distance that camps are moved (Bettinger, 1991; Kelly, 1995), and we might consider residential and logistical land use strategies to be the ends of a continuum of mobility. However, these different strategies involve significant differences in the organization and nature of technologies, social organization and group size, diet, and the distribution of activities (Binford, 1980; Grove, 2009, 2010b; Kelly, 1983, 1992, 1995). Hence, it may be better to consider them as stable attractor states under different ecological conditions (Barton and Riel-Salvatore, 2014).

Among the technological consequences of these different land use strategies is the nature of lithic assemblages that accumulate in forager camps. These differences are described in numerous publications (e.g. Barton, 1998; Barton and Riel-Salvatore, 2014; Riel-Salvatore et al., 2008; Riel-Salvatore and Barton, 2004, 2007) and won't be detailed here. In brief, retouched artifacts are more common in assemblages of lithics discarded at the camps of residentially mobile foragers and much less common in logistical base camps. For a large number of archeological lithic assemblages spanning the last glacial period and distributed across western Eurasia, Riel-Salvatore and Barton identified a long-term trend toward decreasing retouch frequency, indicating the spread of logistical land use strategies among temperate zone foragers of this region (Barton et al., 2011; Barton and Riel-Salvatore, 2012a, 2016). As temperate forests, and diverse and widely distributed subsistence resources were replaced by open steppe-tundra supporting large ungulate herds, humans adopted land use strategies that reduced subsistence risk. This shift took place over a span of nearly 100ka, culminating in nearly universal adoption of logistical strategies by the Last Glacial Maximum. This exemplifies system and complex system resilience in response to low frequency disturbances and long-term stresses, discussed by Martin-Breen and Anderies (2011). These resilient land use strategies, along with new technologies enabled human populations to maintain critical functionality and survive for the first time in temperate zone glacial environments. However, as Martin-Breen and Andries note, long-term complex system resilience may result in significant reorganization or structural change in systems. This was the case in glacial Eurasia.

At the beginning of the last glacial, Eurasia was occupied by a distinct regional population we call Neanderthals. There were probably many such distinctive human populations given that humans were so widespread across Africa, Europe, and Asia by the last interglacial, occupying a niche close to social carnivores. Several other such populations have been identified recently, such as specimens found at Denisova Cave in central Asia (Kaifu, 2017; Kuzmin et al., 2022; Rogers et al., 2017). The taxonomic position of Neanderthals in the human lineage has been debated since the first specimens were discovered. While Neanderthals had a suite of distinctive morphological characteristics, it has been repeatedly remarked that they would probably pass unnoticed in today's cities. Nevertheless, distinct Neanderthal morphologies disappeared worldwide prior to the Last Glacial Maximum. Given mammalian speciation rates and the likely time of geographic semi-isolation (though never completely isolated) in Europe, Neanderthals are probably best considered a regional sub-population or sub-species of *H sapiens*, fully inter-fertile with other contemporaneous representatives of our species (Barton et al., 2011). This assessment has been borne out by paleogenetic studies that show the introgression in modern Europeans of a small number of genes found only in Neanderthals (Dannemann et al., 2016; Green et al., 2010; Sankararaman et al., 2014; Villanea and Schraiber, 2019). This has important implications for the consequences of the resilient responses of humans to environmental risk of the last glacial.

Because logistical land use involves regular long-distance forays to locate patchy, mobile animal resources, it means that logistically organized human groups have an increased opportunity to meet and interact with a wider community of more distant human groups than they would following residential land use strategies. While such interactions could involve conflict, they could also involve the exchange of cultural knowledge, alliances, and the exchange of mates (and genes). The latter can all increase the adaptive capacity of human groups to reduce risk in glacial environments characterized by high uncertainty in environmental conditions, including critical resources, across space and time.

Such mutually beneficial, long-distance interactions could also have other long-term consequences for endemic populations like Neanderthals. Biogeographical changes that increase interactions among different populations of a species (or sister species) can lead to the apparent extinction of one of the populations as a distinct variant (Garrigan and Kingan, 2007; Wolf et al., 2001). In order to test the potential for a similar process to account for the disappearance of Neanderthals in glacial Eurasia, Barton, Riel-Salvatore, and colleagues developed numerical and computational agent-based models with which to carry out experiments in long-term biocultural evolution. These models are detailed elsewhere (Barton et al., 2011; Barton and Riel-Salvatore, 2012a), and the model code is published and openly accessible (Barton, 2011, 2012); we provide only a brief summary here.

We created two populations of agents. All agents in both groups have the ability to forage within a radius from a stationary home base camp, set by the researcher. They do not move in any other way except to forage out from a camp. If an agent encounters another agent while foraging, it can mate and produce an offspring. The offspring will establish a new camp at a random location near the parent but outside of the foraging radius of any other agent. The probability that two agents will produce an offspring when they interact is controlled by a birthrate parameter set by the researcher. All agents also have a probability of death, controlled by a death rate parameter set by the researcher. All agents have a digital "genome" that can be taken to represent biological genes, cultural traits, or a combination thereof. One population begins with a genome consisting only of N/N trait pairs, representing Neanderthals, and the other begins with a genome consisting only of M/M pairs, representing anatomically modern humans (AMH). Neanderthal agents are initially placed randomly in a digital landscape of western Eurasia, while agents representing AMH are placed randomly elsewhere on the digital landscape, adjacent to digital western Eurasia. We carried out multiple experiments in this modeling laboratory, varying foraging radius, initial population sizes, fitness (modifying birth and death rates), assortative mating, and the distance at which other agents could be perceived (Barton et al., 2011; Barton and Riel-Salvatore, 2012a, 2012b). Here we focus on modeling results most relevant to risk and resilience.

Figure 3 shows some of the results of modeling experiments reported in Barton and Riel-Salvatore (2012a). In these experiments, we varied maximum foraging radius from two cells, representing residential land use, to 12 cells, representing highly logistical strategies with long-distance foraging. We also varied relative fitness of agents from different populations and of hybrid offspring resulting from a mating of agents from different populations. All experiments shown began with initial populations of 100 Neanderthal agents, representing the endemic population, and 500 agents of AMG in the rest of the world. All models ran for 1500 "generational" steps and each experimental configuration was repeated 10 times. The boxplots in Figure 3 display the final number of individuals of each "phenotype" category (groups of similar digital "genomes" – see figure caption) for all repetitions of that configuration.

In most narratives explaining the disappearance of Neanderthals, it is assumed that they were in some way less biologically or culturally fit than AMH populations that spread into Europe during MIS 3 in the last glacial. Indeed, in experiments where agents practiced residential mobility, Neanderthal agents go extinct in the two scenarios where they are less fit than AMH agents, including both those with 100% Neanderthal traits (NN phenotypes) and those with 76%–99% Neanderthal traits (N-type phenotypes). Neanderthal and Neanderthal-like phenotypes dominate the final global agent populations where they are more fit than AMN, though AMH agents never go extinct.

The resilient, logistical land use scenarios are more interesting and present results that are counter-intuitive, though corresponding well to available empirical data. Agents with 100% Neanderthal traits go extinct in all configurations, including those in which they are more fit than AMN agents. AMH agents (with 100% AMH traits) go extinct in two scenarios where Neanderthal agents are more fit than AMH agents, but so do Neanderthal agents. The simulated populations in all but one of the most logistical scenarios (i.e. maximum foraging radius) are dominated by AMH agents with some Neanderthal introgression (i.e. "M-type" agents). The evolutionary process that leads to these results can be seen in Figure 4. The results of the modeling, especially logistical land use with the largest foraging radius closely match real-world events that saw the disappearance of recognizable Neanderthals before the Last Glacial Maximum, and introgression of a limited amount of Neanderthal genes into subsequent European populations.

In summary, long-term resilience to mitigate long-term risks of glacial environments of temperate Eurasia enabled humans to survive but resulted in significant system reorganization: the extinction of the original Eurasian human population. Neanderthal descendants with some Neanderthal traits survived, but Neanderthals as recognizable population with distinctive biological and cultural traits did not. In discussions of resilience today, there is sometimes the implication that societal resilience can help distinctive cultural groups to maintain their identity in the face of an increasingly globalized world (e.g. Cumming et al., 2005; Healey, 2006; Rotarangi and Stephenson, 2014). However, Martin-Breen and Anderies (2011) note that resilience may in fact entail a transformation of identity. The study of resilience in deep time described above likewise suggests that system resilience may transform identity. As we conclude in our 2011 paper, "In one sense we could say that their extinction was the result of Late Pleistocene globalization as Neanderthals were biologically and culturally absorbed into a pan-Eurasian genome and cultural sphere. But in another sense, they disappeared because of their ultimate success in adapting to rigorous, rapidly changing glacial environment through culturally driven behavioral change." (Barton et al., 2011: 722). More resilient social practices and technologies indeed can help people mitigate long-term risk, even extreme environmental risk. But if such strategies are successful in adapting to long-term shocks and stresses, they may also have evolutionary consequences including eventual loss of distinctive cultural, or even biological, identity.

Limits to resilience

In another study, we conducted a more focused exploration of risk and resilience in deep time, centered on the western Mediterranean region and the period from the Last Glacial Maximum (LGM) to the early Holocene (Barton et al., 2018). We calculated metrics of environmental uncertainty and risk by combining empirical environmental data with paleoclimate models. We evaluated human risk-mitigating behaviors with data (lithic assemblages, faunal assemblages, and radiocarbon dates) from over 200 archeological assemblages drawn from published literature. This study adds finer grain detail to the more temporally and geographically expansive one described above.

Figure 3. Results of agent-based modeling of interactions between agents representing Neanderthals and anatomically modern humans (AMH). See text and Barton and Riel-Salvatore (2012a) for details of the modeling protocols. Results are calculated after 1500 time steps. Boxes outline dominant agent phenotypes of all model runs for each combination of parameter settings. Red boxes indicate final populations where MM phenotypes dominate, orange boxes where M-type phenotypes dominate, green boxes where MN phenotypes dominate, and blue boxes where NN types dominate. MM phenotypes: 100% M traits, M-type: 76%–99% M traits, MN: 25%–75% M or N traits, N-type: 76%–99% N traits, NN: 100% N traits. See data access statement for availability of model code, data, and analysis scripts.
Note. Please refer to the online version of the article to view this figure in color.

Although the last glacial period was overall more variable climatically than the preceding or current interglacials, the amount variability changed over time, with more and less stable intervals. Somewhat surprisingly, we found that the most climatically intense part of the last glacial, the Last Glacial Maximum, was an interval of comparative environmental stability, with reduced uncertainty and risk for forager groups in this region. The interval of greatest instability, and hence uncertainty and risk, occurred at the end of the last glacial and the transition to the current Holocene interglacial.

We documented how the adoption of highly flexible, portable, and maintainable hunting technology (Bleed, 1986) combined with the ability to shift land use and ecological niche to enabled human populations to withstand repeated environmental shocks of growing intensity. Throughout this period there is increasing use of lightweight, complex, multi-component hunting technology, culminating in technocomplexes variously named Magdalenian, Epigravettian, and Badegoulian. Tiny lithic components (backed bladelets) could be inserted into lightweight bone, ivory, or wood foreshafts of spears and darts propelled by atlatls with high force and accuracy. Lithic assemblage analysis shows and increasing bifurcation between more stable, long-term base camps and distant specialized hunting camps. Faunal assemblages likewise show an increasingly bifurcated hunting strategy, in which small game was taken close to base camps and large game acquired in specialized long-distance expeditions. In one part of the region, southern France, we showed how these late Paleolithic hunters shifted the habitats and game they

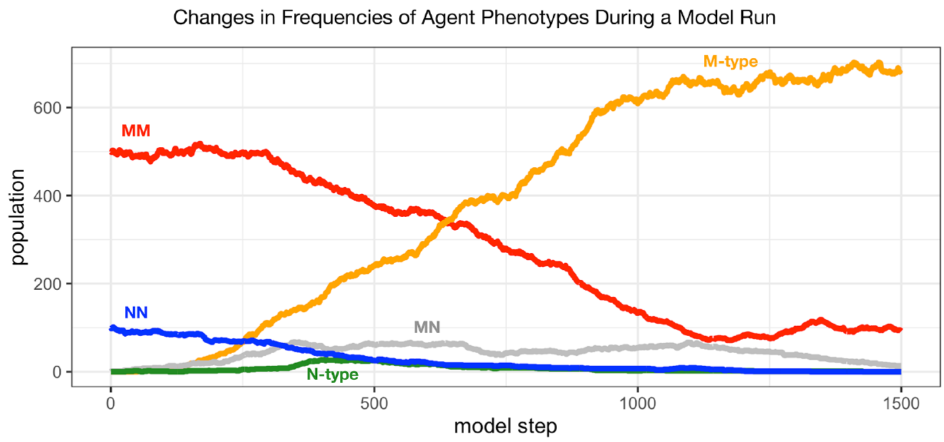

Figure 4. Trajectory of an example modeling run with logistical land use (foraging radius = 12) showing changes in agent populations. Agent phenotypes are the same as in Figure 3.

exploited as climate change drove the replacement of steppe-tundra and its large ungulate herds with temperate forests and dispersed and often smaller game.

Finally, we used summed probability distributions (SPD) of radiocarbon dates as a proxy for human demography to show how this highly resilient suite of technologies and practices enabled long-term stability in human population across the region, and even supported significant population increase in the late glacial. SPD analysis involves mathematically combining the age probability distributions of a series of individual radiocarbon dates into a continuous time series that reflects the frequency of radiocarbon dates over time within a region. Rick (1987) initially proposed that with careful analysis and control of potentially confounding factors, this could serve as a proxy for human population. While there have been critiques of this approach (Bamforth and Grund, 2012; Carleton and Groucutt, 2021; Contreras and Meadows, 2014), increasingly sophisticated protocols and analysis methods have made this one of the best ways to estimate prehistoric demographic trends currently available, in spite of any limitations (Crema, 2022; Crema and Bevan, 2021; McKay et al., 2021; Popescu et al., 2023; Timpson et al., 2021).

This study observed that an apparent end-Pleistocene demographic boom coincided with the most extreme climatic fluctuations of late Last Glacial (Barton et al., 2018). However, the successful social and technological strategies that enabled this population growth eventually were insufficient to cope with the increased uncertainty and risk leading up to the Pleistocene-Holocene transition, resulting in an apparent regional demographic collapse (see also Fernández-López de Pablo et al., 2019). Here, we present a new analysis of this radiocarbon record to offer more insight into longer term dynamics of resilience and its limitations.

Figure 5 shows a new SPD analysis of radiocarbon dates for the Late Pleistocene to early Holocene in the western Mediterranean using the *rcarbon* package (v. 1.5) in R v.4.2.3 (Crema and Bevan, 2021). The SPD curve is compared with a null model of slow exponential growth in radiocarbon dates that represents a combination of slow population growth with the greater likelihood of preservation and archeological discovery of more recent dating samples than older ones, estimated by repeated random draws of dates from the dataset used to calculate the SPD (Crema and Bevan, 2021). Lacking any evidence to the contrary, this is the most parsimonious null model for the lengthy time period and broad regional coverage represented. Comparing the SPD (red line) with this null model (the gray zone is the 95% CI of the model) allows for more robust estimates of when ancient population (for which the SPD is a proxy) was lower or higher than might be expected under null model conditions.

For the period addressed in the 2018 study, the LGM to the early Holocene with calibrated ages of 22ka–6ka, the new SPD analysis largely supports the conclusions of the earlier one. Following a significant demographic decline, population remains largely stable and within the bounds of the null model for the LGM (22ka–18ka), and continues in this way up to through the Late Pleniglacial (19ka–14ka) and most of the End Glacial (14ka–10ka). During the End Glacial (14ka–10ka), however, the SPD curve climbs far above the upper bounds of the null model and then after 13ka drops precipitously to fall below the null model CI at around 11ka, before rebounding in the early Holocene.

For this analysis, we expanded the list of dates used in the 2018 paper to include more earlier dates that allow the new SPD analysis to extend back to 35ka, in late MIS 3. We also corrected textual errors in our original data that have become apparent recently and removed a few dates with now known technical or physical issues that produced unreliable dates. As before, we also eliminated dates in which the standard deviation is unusually high, using the coefficient of variation (i.e. COV > 0.1) as a reliable metric that takes into account the fact that the absolute value of the standard deviation inherently increases with older dates. Likewise, we again binned all dates in 200 year intervals to reduce collection biases (e.g. different investments in archeological research among sites), the Monte-Carlo simulations to create the null model were repeated 200 times, and a 500 year moving window was used to smooth the resulting SPD curve. Details of this analysis are published, along with the data and code to reproduce it, on Zenodo at https://zenodo.org/record/8187662 (Barton et al., 2023).

This expanded dataset provides insight into long-term interactions of risk and resilience, technology, and demography. In addition to the End Glacial demographic crisis describe above and in the 2018 study, it is apparent in Figure 5b that there are two earlier such crises that are longer and as or more intense as the End Glacial one: one at around 27ka and another centered on 22ka. Additional, very short periods in which the SPD barely falls below the null model CI occur around 18ka.

To the extent that the SPD curve serves as a proxy for paleodemography, all three major demographic crises follow episodes of significant climatic variation, and especially decreasing temperatures for the last two, as represented in ^{18}O data from Greenland ice cores (Figure 2); temperature signals are ambiguous for the earliest one. Such demographic crises indicate a loss of resilience, when behavioral strategies and technologies failed to mitigate the severity of environmental risk. However, there are also other intervals of climatic variability and decreasing temperatures that are not coincident with demographic declines. These inconsistencies between the SPD demographic proxy and global glacial ice

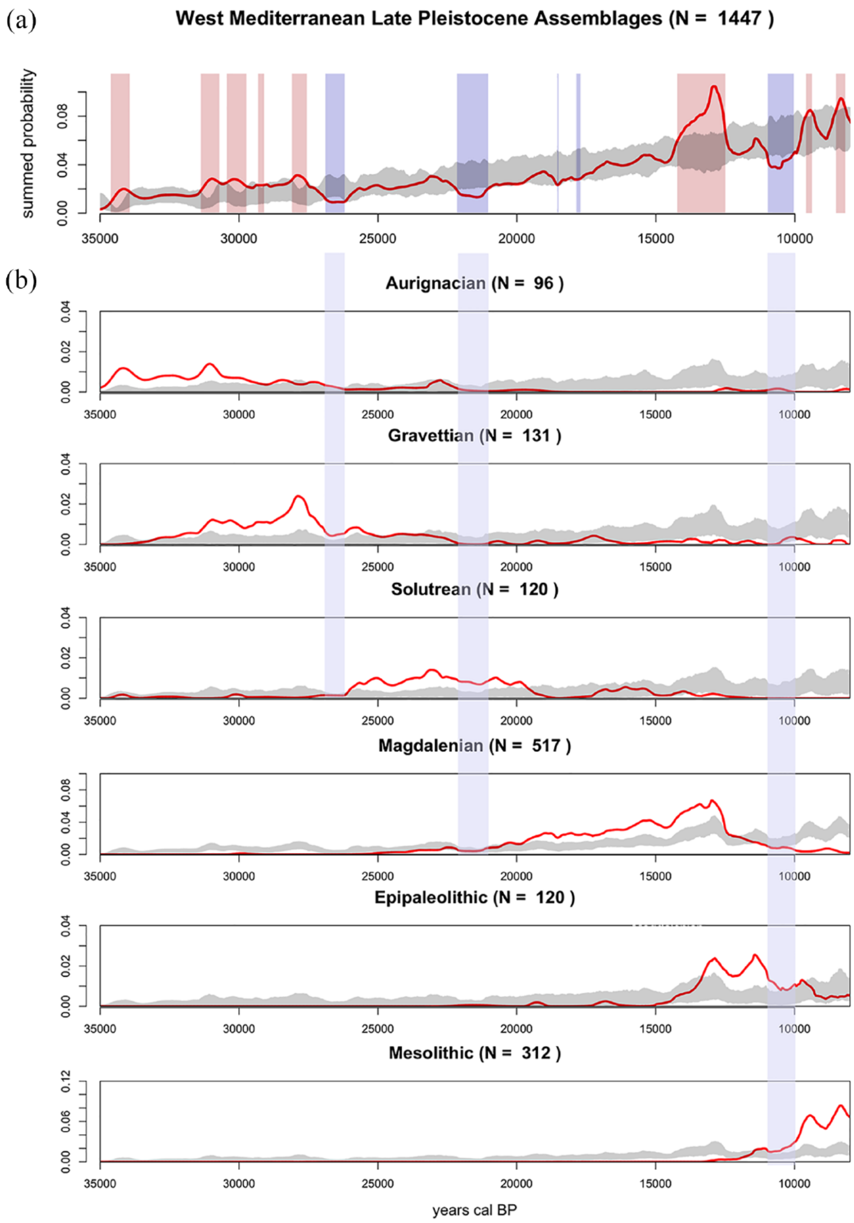

Figure 5. Risk and resilience in the Upper Paleolithic of the western Mediterranean, 35-8ka. (a) Summed probability distribution (SPD) curve for 14C dates of archeological assemblages in western Mediterranean (red line) compared with 95% CI of exponential null model (gray zone, see text). Pale red and blue bands indicate segments of the SPD curve that extend above and below the null model 95% CI respectively. Blue bands are also extended onto graphs below (5(b)) for comparison. (b) SPD curves for major named archeological technocomplexes in the western Mediterranean displayed as a random permutation test (see text). Gray 95% CI envelope represents a "background" model generated from all dates. Periods when each SPD falls outside this envelope indicates a significant departure from this background. Local/regional names for morphologically and chronologically similar technocomplexes are aggregated to show pan-regional patterning: Aurignacian, Gravettian, Solutrean (*Solutrean*, *Salpetrian*, and *Solutreo-Gravettian*), Magdalenian (*Magdalenian*, *Badegoulian*, and *Epigravettian*), Epipaleolithic (*Azillian*, *Romanellian*, and generic *Epipaleolithic*), and Mesolithic (*Castelnovian*, *Montadian*, *Montclusien*, *Sauveterrian*, *Tardenoisian*, and generic *Mesolithic*). See data access statement for availability of data and analysis scripts.
Note. Please refer to the online version of the article to view this figure in color.

volume (a primary driver of variation in $^{18}O/^{16}O$ ratios in these ice cores) is likely in part an indication that prehistoric inhabitants of the western Mediterranean were most directly affected by local terrestrial environmental changes that were only indirectly linked with distant glacial advances and retreats. However, they are also evidence of socio-technological systems that were resilient to at least some environmental shocks and stresses. Examining the chronological distribution of associated archeological data provides additional insight into these dynamics and raises new questions.

Also shown in Figure 5b are SPDs of major named Upper Paleolithic technocomplexes of this region. Technocomplexes with regionally different names but similar artifacts and chronologies have been aggregated into unified categories (see Figure 5 caption, and data and analysis scripts). This grouping should be considered a preliminary approximation at best, given the considerable inconsistencies in artifact classification and naming conventions in Paleolithic archeology (Barton and Clark, 2021; Clark and Riel-Salvatore, 2006; Reynolds and Riede, 2019; Shea, 2019). We also recognize potential uncertainties in the association of material dated with lithic industries that can occur even in the most carefully excavated sites. Hence, for this series of SPDs, we removed any date in which the associated lithic industry was not clearly specified, published, or supported by artifactual evidence; we did not remove dates simply because they seemed too old or too young for the published, associated industry. Nevertheless, the SPD curves for these rough groupings are informative by showing long-term trends for each technocomplex to more robustly identify these trends, we used the *rcarbon* Random mark permutation test for SPDs (*permTest* module). This module randomly shuffles radiocarbon dates grouped into categories ("marks") to simulate a "background" SPD, with a 95% confidence interval, for dates from all categories combined. It is then possible to compare the SPD for each date category (technocomplexes here) against this background to identify where it falls outside the background.

Across all of these technocomplexes, there is considerable continuity in lithic technology (e.g. blade production from prepared cores), processing tools (e.g. end scrapers, side scrapers, burins), evidence for working of non-lithic materials like wood and bone, and the presence of representative imagery (e.g. mobile and parietal art). There are also general trends for increasing control of production, standardization, and elaboration of many forms of material culture – for example, from the large blades and non-standardized backed pieces in the Aurignacian to the highly standardized, backed bladelets in the Magdalenian. The major differences in these technocomplexes, beyond regional naming conventions, is primarily in the design of hunting weapons and related artifacts. For example, backed blades and flakes of the Aurignacian and Gravettian were probably mounted in wood spears, or wood or bone foreshafts of spears. The Solutrean represents a different way to manufacture hunting weapons using bifacially worked blades and flakes, and unifacial or bifacial stemmed points (i.e. notched/shouldered points) to tip weapons. The Magdalenian takes a yet different approach, using very small, standardized, backed bladelets mounted in wood, bone, or ivory shafts and augmented by elaborate bone harpoons and antler atlatls. These technocomplexes were likely embedded in equally sophisticated socio-ecological-technological systems for which we have less clear evidence in the archeological record (Barton et al., 1994; Clark et al., 1996; Fitzhugh, 2001; Gravel-Miguel, 2016; Romano et al., 2022; Whallon, 2006).

That is, these industries represent the preserved remnants of different socio-technological strategies to mitigate ecological risk and maintain resilience to environmental shocks of the last glacial. For example, there is spatial-temporal evidence, that the spread of Solutrean projectile tips is associated with the expansion of steppe-tundra and its large ungulate fauna that accompanied the maxima continental ice sheet advance in the LGM (Barton, 2013; Tiffagom et al., 2007). The resilience of these Paleolithic systems can be seen in the multi-millennial spans between the demographic downturns seen in the SPD and null model graph. Interestingly, the ends of major demographic crises in the long-term SPD for the western Mediterranean coincides with the initial spread of a new technocomplex. This is especially apparent with the initial spread of the Solutrean, Magdalenian, and Mesolithic. Where the initial spread of a new technocomplex does not follow a significant demographic decline there is considerable chronological overlap with a preceding technocomplex (i.e. much of the Gravettian overlaps the Aurignacian; the same is true for the Magdalenian and Epipaleolithic) suggesting equivalence in the effectiveness of the overlapping technocomplexes for the environmental conditions of the relevant time interval. The beginning of the Aurignacian cannot be assessed in this way because the SPDs analyzed here do not extend beyond 35ka.

This is another example of the kind of long-term system resilience discussed above. There are several insights to be drawn from these data and analyses. One is that resilient socio-technological systems seem to have a limited lifetime, even if a long one in terms of human lifespans. Systems that proved resilient over millennia of environmental uncertainty and risk must be considered highly successful. However, all of these systems eventually encountered conditions with which they could not cope – whether due to environmental extremes exceeding the adaptive capacities of these systems, inherent vulnerabilities of systemic risk that were eventually triggered by exogenous or endogamous conditions, or some combination of both – resulting in significant demographic impacts that lasted centuries. Additionally, recovery from these demographic crises was associated with technological innovation, likely coupled with innovation in social forms and cultural knowledge. At the very long-term scale of almost 30ka represented here, we can see cycles of resilience that involve repeated recovery from significant environmental stress, maintaining critical functions to support human life while requiring significant reorganization of human systems.

While this kind of cycle could be fit into the descriptive panarchy model of Gunderson and Holling mentioned previously (Gunderson and Holling, 2001; Redman, 2005; Redman and Kinzig, 2003), a more directly relevant mechanism for forager ecology and resilience has been proposed recently by Freeman and colleagues (Freeman et al., 2023). In this *Adaptive Capacity Trade-off* model initial success of a socio-technological system in providing resources leads to population increase. As population and resources approach imbalances, due to population growth and/or environmental change, adjustments to social and technological components are made. But over time, these are increasingly subject to diminishing returns due to path dependence in both components. Foragers can overcome these limits in the short term through increasing the time and energy spent foraging, but the combined effects leave them increasingly vulnerable to shortfalls and demographic crises, especially in a temporally variable environment. These "recessions", as Freeman and colleagues term such demographic crises, can lead to migration and generate incentives for significant socio-technological innovation. They provide SPD data from the Holocene of Texas, USA to illustrate these resilience cycles that are similar in overall pattern and frequency to those we document here for the late Pleistocene of the western Mediterranean.

Resilience and systemic risk in coupled socioecological systems

We might well ask if the insights drawn from the previous examples represent dynamics that are generalizable beyond the ancient systems studied – an important question if historical sciences hold a potential to provide insights about today's world and help plan for the future. Can system resilience to long-term environmental stresses result in reorganization so profound that a system loses its prior identity? When do conditions become so uncertain and extreme that they exceed the adaptive capacity of a system to mitigate risk? What are the processes by which a system that is no longer resilient at mitigating risk is able to create technological innovation that restores resilience? That is, is necessity really the "mother of invention"? Or is archeology only able to perceive the successful innovation that restores resilience and not the many other failed attempts that left a system in crisis? Is the Upper Paleolithic case study presented above an example of very long-term panarchy cycles that Gunderson and Holling, 2001; Redman and Kinzig, 2003) proposed for ecosystem dynamics?

Even in forager societies that seem simple compared with modern urban life, resilience and its consequences are the result of complex interactions in among cultural knowledge and its social transmission, operationalizing that knowledge in behavior (including the creation and use of technology), and multiple biophysical components of the natural environment. The multi-dimensional, simultaneously operating feedbacks, along with non-linear and often indirect connections between cause and effect in these complex socio-ecological-technological systems can make the long-term outcomes of short-term risk mitigation difficult to anticipate intuitively, as illustrated in the first case study above. The concept of systemic risk involves the recognition that dynamic complex systems may have inherent vulnerabilities to some risks in spite of,

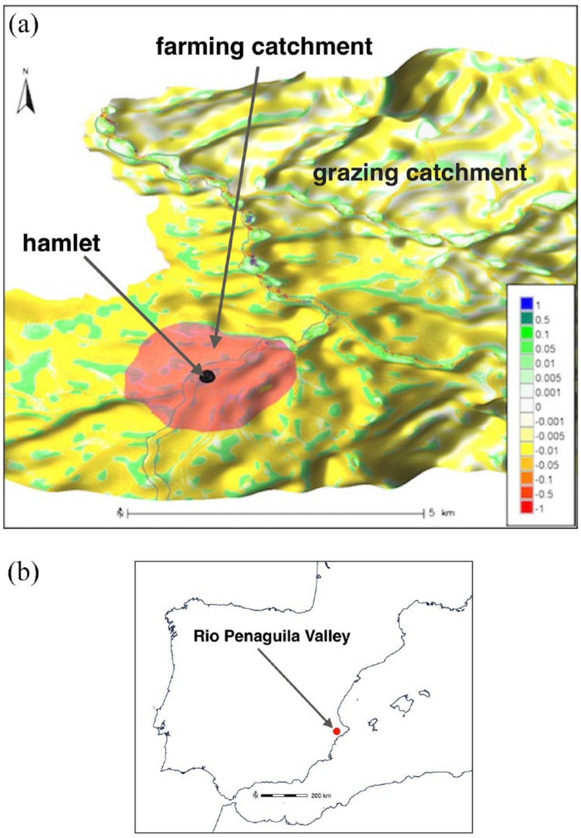

Figure 6. (a) Digital landscape for integrative modeling of agropastoral land use and landscape change. Digital topography of Rio Penaguila valley shown, overlayed with location of hamlet, zone of shifting cultivation for cereals, and colors indicating meters of sediment eroded or deposited after 200 annual time steps. (b) location of Rio Penaguila valley.

or even because of, their resilience to others. In order to successfully apply insights from deep time to risk and resilience today, it is necessary to be able to trace down-the-line system responses to changes in interacting components. Study of the single, realized outcome from the real-world past is not sufficient to accomplish this; it is also necessary to study alternative outcomes that could have happened but did not. This requires augmenting our innate interpretive abilities with comparatively new analytical tools of mathematical and especially computational modeling and simulation (Cegielski and Rogers, 2016; Romanowska et al., 2021).

The first case study above exemplifies the potential value of approach. In the real-world past, Eurasian Neanderthals adapted their land-use strategy to be more logistical, apparently in response to environmental changes of the last glacial period, and disappeared as a morphologically and genetically distinct population. More importantly, the modeling described above strongly suggests that as an endemic population within temperate zone western Eurasia, that faced significant bioclimatic change and loss of inhabitable land area as ice sheets spread over the region, Neanderthals were probably doomed to extinction regardless of their resilience. Prior populations lacking Neanderthal adaptive capacity seem to have disappeared during glacial advances. Adaptive land-use strategies led to extinction, even when Neanderthals had greater biological fitness than AMH elsewhere. Even if Neanderthals had managed to survive while maintaining more insular land-use, modeling not shown in Figure 3 indicates that they would still disappear if AMH alone adopted logistical strategies (Barton et al., 2011).

Today, such modeling is becoming an increasingly important tool for evaluating alternative futures (Masson-Delmotte et al., 2021). In a globally interconnected world, with a human population nearing eight billion, and with behaviors and technology that have significant impacts on planetary biophysical systems (Ellis et al., 2013; Steffen et al., 2015), it is critical that this modeling attempt to capture the complex interactions among people and between people and the environment in order to assess current and future risk (including systemic risk), and build resilience to mitigate those risks (Robinson et al., 2018). Applying modeling to societies in deep time can play an important role in helping us better understand the processes that generate risk and resilience in socio-ecological-technological systems, and their long-term evolutionary dynamics.

The Mediterranean Landscape Dynamics Project (MedLanD) is an interdisciplinary research initiative to understand the socio-ecological-technological dynamics that resulted in the emergence of coupled natural and human landscapes. To accomplish this, the MedLanD Project integrates archeological and paleoecological fieldwork, geospatial analytics, and computational modeling (Barton et al., 2011, 2012, 2015b, 2016; Diez Castillo et al., 2008; García Puchol et al., 2015; Mitasova et al., 2013). The MedLanD Modeling Laboratory (MML), dynamically couples models simulating small holder agropastoralism, geophysical landscape evolution, anthropogenic and natural fire, and vegetation land cover in order to study the long-term outcomes of socio-natural feedbacks.

The MML approach of coupling models of societal and geophysical processes remains rare, in spite of widespread recognition of the significant impacts of humans on the Earth system (Calvin and Bond-Lamberty, 2018; Rounsevell et al., 2014; Verburg et al., 2016). As part of a review of current efforts to model feedbacks between human and natural system, and the potential for such integrative modeling to help assess and mitigate systemic risk (Robinson et al., 2018), the MedLanD team undertook a series of computational modeling experiments in the MML. These experiments were designed to explicitly compare the results of modeling of feedbacks between human and biophysical systems, with modeling those systems independently. The experiments were configured following protocols used previously to explore the impacts of small holder agropastoralism on the formation of *barrancos*, erosional channels common in the landscapes of Mediterranean Spain (Barton et al., 2015a).

All experiments took place in a digital landscape represented by a high-resolution DEM (digital elevation model) of the Rio Penaguila valley, in northern Alicante Province (Spain), where the presence of Early Neolithic agropastoralists has been documented (Figure 6). Initial landcover of the entire digital landscape was set to the equivalent of Mediterranean woodland in all experiments, representing the pre-Neolithic condition as reconstructed from paleoenvironmental studies in the region. For comparative purposes, we ran a non-anthropogenic "control model," that did not activate the human systems model in order to simulate what might have occurred without human activity to alter the landscape. The agropastoral system model was initiated with a hamlet of 200 agents, located geographically at the early Neolithic site of Mas d'Is (Bernabeu Aubán et al., 2008; Bernabeu Aubán and Orozco Köhler, 2005). Based on caloric needs and population size, agents could choose land (grid cells) for shifting cultivation within walking distance to the hamlet (clearing, cultivating, or fallowing cells), or for ovicaprine grazing at greater distances within the valley. Each simulation ran for 200 annual time steps to reveal long-term system dynamics that require historical or archeological records to be studied empirically. For the new series of experiments to model feedbacks, we altered the original protocols so that one suite of model runs would take place with human and biophysical systems completely decoupled, another with unidirectional coupling from the human systems model to the landscape model, and a third set of experiments with full bidirectional

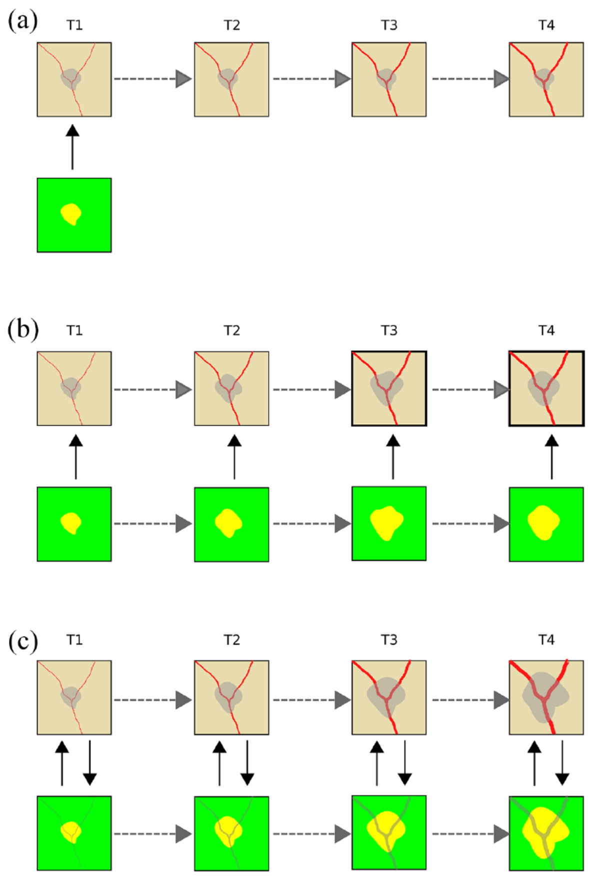

Figure 7. Schematic of three sets of experiments: (a) Static land use patterns are unchanging inputs into dynamic landscape model. (b) Evolving land use, generated from dynamic agropastoral model is input to dynamic landscape model at each annual time step. (c) Evolving land use, generated from dynamic agropastoral model is input to dynamic landscape model, and landscape modeling results (topography, soils and their fertility, vegetation cover) are input to agropastoral model at each annual time step. See text for more details.

coupling between human and biophysical system models. This is shown schematically in Figure 7.

- For the decoupled modeling experiments (Figure 7a), we ran the agropastoral model with 10 different configurations, representing increasing human pressure in the farming and grazing catchment, that generated an equal number of land use patterns identifying landscape cells as cleared for farming, cultivated, fallowed, or used for ovicaprine grazing. Each resulting land use pattern served as input parameters for the landscape evolution and landcover models.
- In the partly coupled experiments (Figure 7b), we ran one configuration of the agropastoral model simultaneously with the landscape evolution and landcover models. Land use results at each model step were used as input to the biophysical models. Humans impacted the modeled landscape, but landscape change did not impact the human system model. This experiment was repeated 30 times to allow for potential landscape variability due to stochasticity in the locations of cells chosen by the agropastoral model for different forms of land use.
- In the fully coupled model (Figure 7c), land use from the human system model served as input to the biophysical systems models. Likewise, the evolving landscape and landcover was input to human decisions about land use and resulting agropastoral returns – with positive or negative consequences for modeled human demography, and, in turn, land use decisions. That is, this experiment modeled bidirectional feedbacks between human and natural systems.

The results of these modeling experiments are shown in Figure 8. The non-anthropogenic control model is indicated by the blue lines in each of the graphs. The results of each individual experiment are shown by fine gray lines. Means of the 30 repeated experiments with partial and full coupling are shown as heavier red lines.

For the uncoupled human and natural systems in the first set of experiments, a series of different agropastoral system configurations created different land use patterns. These, in turn, resulted in different landscape outcomes, represented in Figure 8a as cumulative deposition (top half of the graph) and erosion (bottom half). Each land use pattern generated a different linear response in terms of erosion and deposition, a not unsurprising result. This kind of independent modeling of human systems and biophysical systems is common today and can be seen in summaries of alternate climate futures modeled with different inputs of anthropogenic greenhouse gasses (e.g. Pachauri and Mayer, 2015).

In the partly coupled modeling experiment, a human systems model with a single set of input parameters was repeated 30 times. Although landscape change had no impact on perceived or realized agropastoral productivity and the same overall decisions were made in each repetition, stochasticity in the human systems algorithm meant that different landscape cells were chosen for clearance, cultivation, fallowing, grazing, and firewood collection. Nevertheless, all individual modeling outcomes – the almost imperceptible gray lines – very closely conform to the mean of the 30 repeated runs (Figure 8b). Unlike the first set of experiments, however, the landscape responds in a non-linear way to agropastoral land use. There are notable changes in the rate of deposition and erosion at 60–80 years into the simulation, with more subtle changes after that. In other words, partial, one-way coupling of a dynamic human systems model with a dynamic model of biophysical processes enables us to identify non-linear landscape responses to land use that are invisible when socio-natural interactions are not represented.

A human systems model with the same set of input parameters used in the partial coupling experiment was repeated 30 times for the third set of experiments. With complete coupling, landscape changes resulting from human land use alter the landcover and soils. These in turn affect the potential returns from cultivation and grazing, population size, and subsequent land use decisions. These bidirectional feedbacks simulate the co-evolutionary dynamics of interacting human and biophysical systems. The non-linear responses of landscape evolution to land use, visible in the partly coupled model output, can be seen here too (Figure 8c). But while the mean of all model repetitions closely matches that for partial coupling, each individual model repetition deviates noticeably from the mean, even though all began with the same set of input parameters. Some result in erosion and deposition an order of magnitude greater than the mean, while others approach the values generated by the control model with no human impact.

Currently, much risk assessment operates like the first set of modeling experiments. Historical information is collected for a particular risk and contextual variables, and then projected linearly into the future – for example, automobile accidents in different age groups, the frequency of floods in a river valley, or crime rates in different neighborhoods. This is useful, of course, and can help mitigate many forms of risk. However, human and natural systems are inherently dynamic, meaning that risks may not be linearly related to potential causal factors. Moreover, when multiple causal factors are interconnected with non-linear feedbacks,

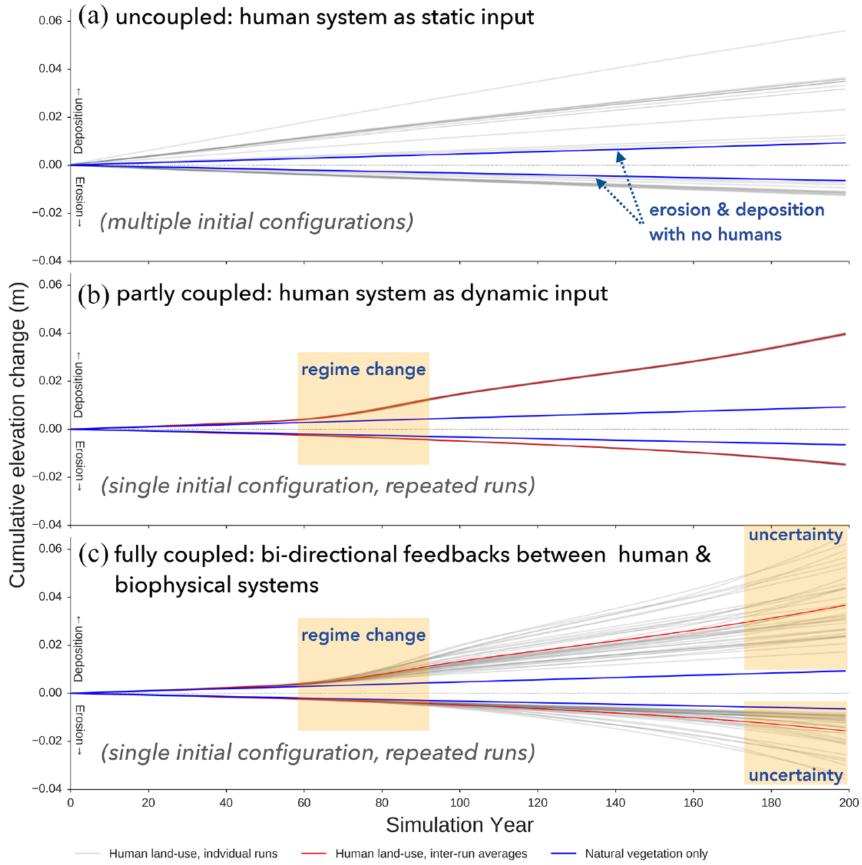

Figure 8. Results of modeling experiments shown schematically in Figure 7. Lines with positive numbers (top half of each graph) indicate mean cumulative meters of sediment deposited across entire digital landscape; lines with negative numbers (bottom half of each graph) are the equivalent mean cumulative meters of erosion. Dark blue lines indicate control landscape evolution model without agropastoral land use. (a) Each fine gray line is a different, static land use pattern generated by the agropastoral land use model. (b) Heavier red line is the mean of 30 repetitions of a single configuration of the agropastoral land use model used as dynamic input to the landscape model; fine gray lines of each individual repetition are almost imperceptible around mean. Temporal occurrence of regime shift in rates of erosion and deposition shown with tan shading. (c) Same as in (b) except that individual model repetitions diverge markedly from group mean indicating wide range of uncertainty in landscape outcomes from a single land use configuration. See data access statement for availability of model code.
Note. Please refer to the online version of the article to view this figure in color.

as is the case for systemic risk, the potential for high levels of uncertainty in the outcomes of a single set of known causal factors make evaluating risk and developing resilient strategies to manage it much more challenging.

Even more important is the value of a deep time perspective for fully assessing risk and resilience, especially for systemic risk. In the last two sets of experiments described above, the rates of landscape change with agropastoral land use, closely match those of the non-anthropogenic control model for the first 50 years. If the experiments had stopped at this point, we might interpret the result to indicate that small holder agropastoral land use has very little impact on landscapes, and is similar in magnitude to the dynamics of "natural" ecosystems. Many risk assessments use periods of less than this. For example, the "normal" weather conditions, often used to estimate the frequency of storms, heatwaves, and precipitation amounts, is based on a 30 year moving average (Gent, 2022). It is only after 60 years in the modeling experiments that landscape change begins to diverge noticeably from the control models, and after 70 years that the uncertainty in outcomes of the last set of experiments begins to appear. This uncertainty is itself non-linear, with rate changes over the total two century span of the last suite of modeling experiments.

Discussion

Risk and resilience both deal with preparing for an invisible future. Also, they can only be assessed by looking backward into an equally invisible past. Written documents are essential to acquiring the information needed to estimate risk and evaluate the resilience of risk-managing strategies in many cases today. However, such documents are only available for a relatively limited part of the recent human past and very often do not record the information needed to make assessments of risk and resilience. Furthermore, many forms of environmental and societal risks occur at low temporal frequency or are stresses that accumulate over time frames of decades to centuries to millennia. This is equally true of systemic risk, where inherent vulnerabilities "baked into" complex, dynamic systems may not become apparent for many years (Tainter, 2006; Tainter and Crumley, 2007). Likewise, evaluating socioecological resilience may involve time frames of decades, centuries, or millennia (see also Riris and de Souza, 2021). Fortunately, the invisible past also leaves material traces that can provide invaluable information about the occurrence and magnitude of long-term risks, as well as the effectiveness of socio-ecological-technological systems at devising resilient strategies to manage risks. The historical sciences, including archeology, have the unique expertise to identify and analyze such traces.

Archeology has the potential to make critically important contributions to understanding and forecasting social and environmental risk, especially long-term risk, as well as designing policies to manage such risk. But not all archeological practice is equally suited to realizing this potential. Traditionally, archeology has involved the subjective interpretation of artifacts to create subjective narratives of past human societies, practices that remain widespread in the field today (Barton, 2013). Such "just so" stories are valuable of course, inspiring the imagination and raising awareness of the diverse tapestry of the human past. But they are much less useful for assessing risk or planning resilience; they are limited to offering cautionary tales of ancient successes and failures rather than robust measures of risk, resilience, and uncertainty. At best, such interpretive narratives could be considered hypotheses awaiting systematic testing to evaluate their reliability.

In order to provide its unique, deep-time insights on risk and resilience in human socio-ecological-technological systems, archeologists must employ rigorous empirical testing of hypotheses about past systems rather than treating interpretations as fact, focus on understanding social and cultural processes that generate system dynamics rather than painting narrative snapshots of ancient life, employ advanced data analytic methods rather than relying primarily on qualitative description, and make full use of computational tools like geospatial technologies and simulation modeling. Fortunately, there are many archeologists who are now embracing these approaches (e.g. Cegielski and Rogers, 2016; Freeman et al., 2023; Gillings et al., 2019, 2020; Pardo Gordó and Bergin, 2021; Riris and de Souza, 2021; Rogers and Cegielski, 2017; Romanowska et al., 2021; Ullah et al., 2023; Verhagen and Whitley, 2020, to list just a few examples). The case studies presented here are but a few examples of such work being carried out by archeologists today. In fact, within the social sciences, archeologists often have been at the forefront of adopting and developing advanced approaches to understanding long-term dynamics of human cultural and societal systems – from statistics (Spaulding, 1953), to computers (Gaines, 1974; Whallon, 1972), GIS and remote sensing (Allen et al., 1990), and modeling (Kohler, 1978; Kohler and Gumerman, 2000; Lake, 2000). That this side of archeology as a rigorous scientific endeavor, with the ability to offer unique and powerful contributions to meeting grand challenges facing humanity today, is less known than it should be is perhaps a testament to the compelling imagery of stories of the past. We hope that the work presented here and elsewhere in this special volume can help to rectify this perception.

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Author contributions

Barton wrote initial text of this paper and co-authored all case studies. He also carried out the modeling in the first case study and the SPD analyses in the second case study. Riel-Salvatore co-authored first case study (Resilience and biocultural evolution), and contributed edits and revisions to the text of this manuscript. Aura-Tortosa, Garcia-Pucho, and Riel-Salvatore co-authored the second case study (Limits to resilience), and contributed edits and revisions to the text of this manuscript. Ullah co-authored and carried out the modeling for the third case study (Resilience and systemic risk), and contributed edits and revisions to the text of this manuscript. All authors contributed data, citations, and references.

Accessibility of data and analysis methods

Data and analysis scripts for the first two cases studies reported are published and openly available at the Zenodo archive: https://zenodo.org/record/8187662. If these data or analysis scripts are used, they should be cited as (Barton et al., 2023).

Barton et al. (2023) Lessons for an Invisible Future - Data Files and Analysis Scripts. Zenodo. Available at: https://zenodo.org/record/8187662: doi:10.5281/ZENODO.8187662.

Model code for the first case study is also published and openly available in the CoMSES.Net Model Library: https://www.comses.net/codebases/2639. If this code is used, it should be cited as (Barton, 2012):

Barton (2012) Hominin ecodynamics v.2. NetLogo. CoMSES Computational Model Library: Arizona State University. Available at: https://www.comses.net/codebases/2639/.

Model code for the third case study is published and openly available at the Zenodo archive : https://zenodo.org/record/7236179. If this code is used, it should be cited as (Barton et al., 2022):

Barton et al. (2022). comses/MML-Lite: MML-Lite v1.0.0. https://doi.org/10.5281/ZENODO.7236179.

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Note

1. Here complex systems (or complex adaptive systems) refers to an interconnected network of interacting entities, characterized by feedbacks, emergent properties, and characteristic organizational properties. This is not to be confused with social and political complexity, characterized by monumental buildings, economic specialization, political hierarchies, warfare, etc. Complex societies are indeed examples of complex systems, but so are non-complex human societies (for more comprehensive discussion, see Barton, 2014; Bentley and Maschner, 2007)

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